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AUTHOR(S): D. HYWEL WHITE

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Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

NEUTRINO OSCILLATIONS

D. Hywel White
Los Alamos National Laboratory
Los Alamos, NM 87545

ABSTRACT

The present status of searches for neutrino oscillations is described at accelerators, reactors and in neutrino sources in the atmosphere. There have been searches for $\nu_e \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_\tau$, ν_μ and ν_e disappearance. There are no compelling signals for neutrino oscillation at this time.

INTRODUCTION

In this paper we shall review the present evidence from searches for neutrino oscillations. There is no clear evidence at present for neutrino oscillations and so the discussion will center on the limits that are set by experiments to date. Experiments come in two categories, those that search for the appearance of a second neutrino flavor in a nearly pure beam, and those who verify the variation of flux from the neutrino source to see if anomalous variation indicates that neutrinos of the dominant flavor are disappearing from the beam.

The standard view of neutrino types is that there exists three flavors, ν_e , ν_μ , and ν_τ : flavor is approximately conserved and the experiments that are reviewed here search for deviations in beam constituents as a function of distance from the source. The probability that neutrinos of one flavor will be observed in a beam of another flavor is

$$P = \sin^2(2\alpha) \sin^2(1.27 \Delta m^2 l/E)$$

where $\sin^2(2\alpha)$ is the mixing angle between dominant production and minority appearance, Δm^2 is the mass difference squared between the two eigen states in a situation where only two flavors are involved in eV^2 , l is the distance from source to point of detection in km, and E is the neutrino energy in GeV. Three state mixing has been discussed at length for example by Marciano⁽¹⁾. Experiments are designed to measure the probability of appearance P or at least to set a limit on P . If we write $P = x \sin^2 by$, where $b = 1.27 l/E$ then for a fixed value of P the curve traced out by coordinates x and y bound the region of exclusion in the $\sin^2(2\alpha) \Delta m^2$ plane. In practice experiments have finite resolution in b so that the region of exclusion is given by

$$x = 2 P / (1 - \cos(2by) \sin(2by\delta/(2by\delta)))$$

approximating the resolution function by a rectangle of width δ .

This curve is illustrated in Fig. 1 and will be familiar to anyone who has heard a talk on neutrino oscillations. The maximum sensitivity (x is Minimum) is when $\cos 2by = -1$, $x = P$ when $\Delta m^2 = \pi E/2l$; for 1 GeV and 1 km $\Delta m^2 = 1.57 \text{ eV}^2$. At high Δm^2 , $x = 2P$. These rules of thumb will allow the casual observer to interpret the results of experiments in different energy and distance regimes.

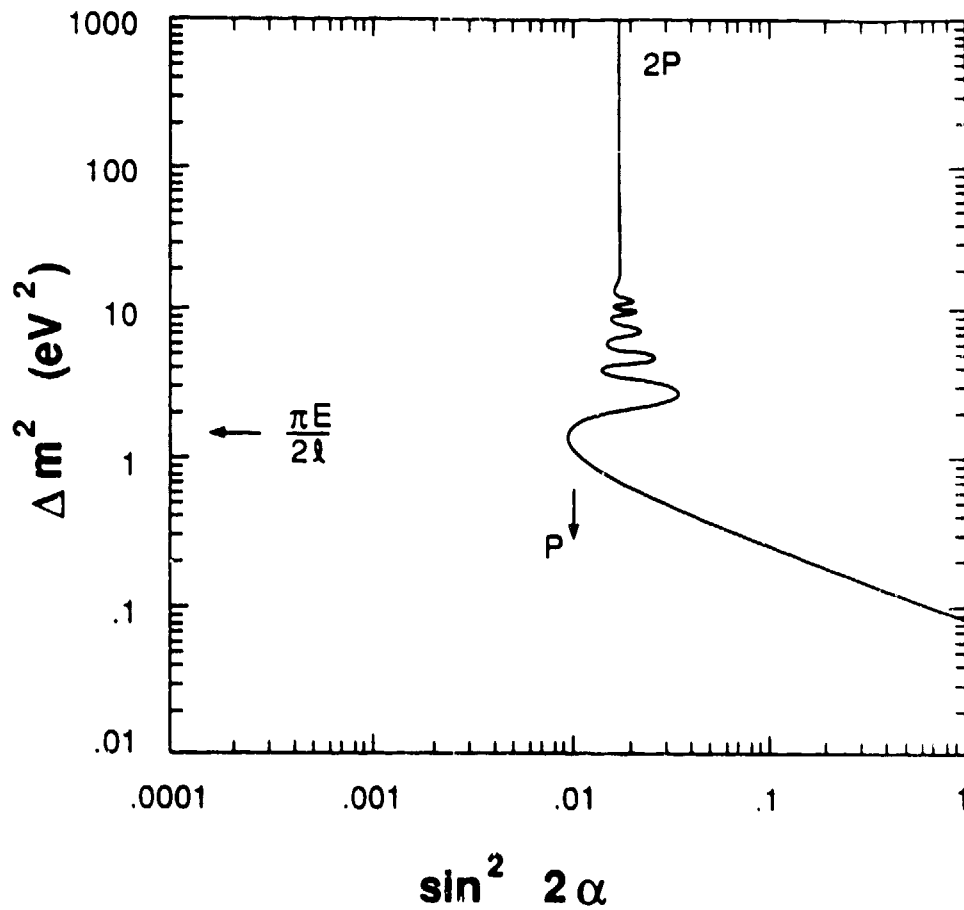


Figure 1

DECAY IN FLIGHT BEAMS, ν_e APPEARANCE

For decay in flight beams at accelerators the most recent limits are given in Table I.

		TABLE I				Ref
		$\langle mE_\nu \rangle$	l	l/E	2P	
BNL	E734	1300	120	0.1	3.4×10^{-3}	2
	CIJH	1300	800	0.8	2.0×10^{-2}	3
CERN	BEBC	1100	825	0.9	2.3×10^{-2}	4
Los Alamos	E764	150	30	0.45	1.5×10^{-2}	5

The region of exclusion of these experiments is shown in Fig. 2.

We have omitted two experiments which observed excess electron events at a statistically marginal level (2.5σ), CERN PS 191 and BNL E 816⁽⁶⁾ although each time with very different numbers of events. It is now believed that these anomalies may be real and ascribed to insufficient knowledge of the low energy region of the neutrino spectrum where the situation is complicated and difficult to measure precisely.

PION DECAY AT REST, $\bar{\nu}_e$ APPEARANCE

In a heavy element beam stop the only decays are

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

because π^- are 99% absorbed in the target no $\bar{\nu}_e$ are produced, (only 1% decay in flight).
A search for the reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

giving electrons between 30 and 50 MeV provides a sensitive way to search for $\bar{\nu}_e$ appearance, presumably from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations. Experiment E645 at Los Alamos⁽⁷⁾ has given a limit shown in Table II and in Fig. 2.

TABLE II

		$\langle E_\nu \rangle$	l	l/E	2P
Los Alamos	E645	40	26	0.65	1.3×10^{-2}

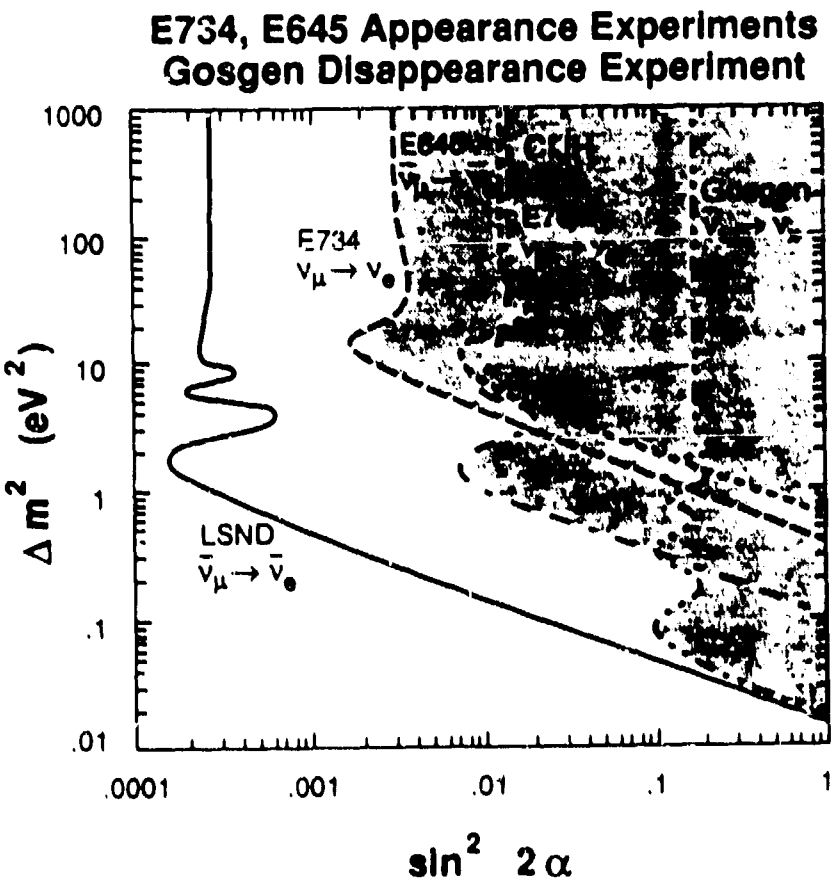


Figure 2

There is an experiment under construction at Los Alamos (LSND) to improve this limit by increasing the mass of the detector by a factor of ten and acceptance by a factor of five. A low decay in flight efficiency also gives a small ν_e background in the beam, so the decay in flight limit for $\nu_\mu \rightarrow \nu_e$ is also expected to be significantly improved over those in Table I⁽⁸⁾. The expected limits are also shown in Fig. 2.

DECAY IN FLIGHT, ν_τ APPEARANCE

Experiments that search for anomalous electron events to limit oscillations can also be used to set limits on $\nu_\mu \rightarrow \nu_\tau$ oscillations because of the decay mode $\tau^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\tau$ gives excess electrons. The sensitivity of these searches is less than $\nu_\mu \rightarrow \nu_e$ directly because of the branching ratio of τ decays to electrons ($\sim 4\%$). A direct search has been conducted at Fermilab (E531)⁽⁹⁾ detecting ν_τ events by observation of a "kink" near the production vertex in emulsion. There is very low background since ν_τ are expected only from charm decay J/ψ , D_s . The sensitivity of the measurement is limited by the counting rate for neutrino events in the emulsion stack and the threshold energy needed to create τ charged current events, the region of exclusion is shown in Fig. 3. A new experimental proposal⁽¹⁰⁾ has emerged using a proposed Fermilab new injector at 130 GeV which gives significantly more neutrino flux than otherwise at Fermilab. The proposal uses improved event detection to ease the scanning problem with scintillating fibers between emulsion stacks and the apparatus all immersed in the magnetic field of the old 15' bubble chamber magnet. The oscillation $\nu_\mu \rightarrow \nu_\tau$ is particularly attractive as a way to solve the dark matter problem with a ν_τ mass in the range of tens of electron volts together with relatively light ν_μ and ν_e .

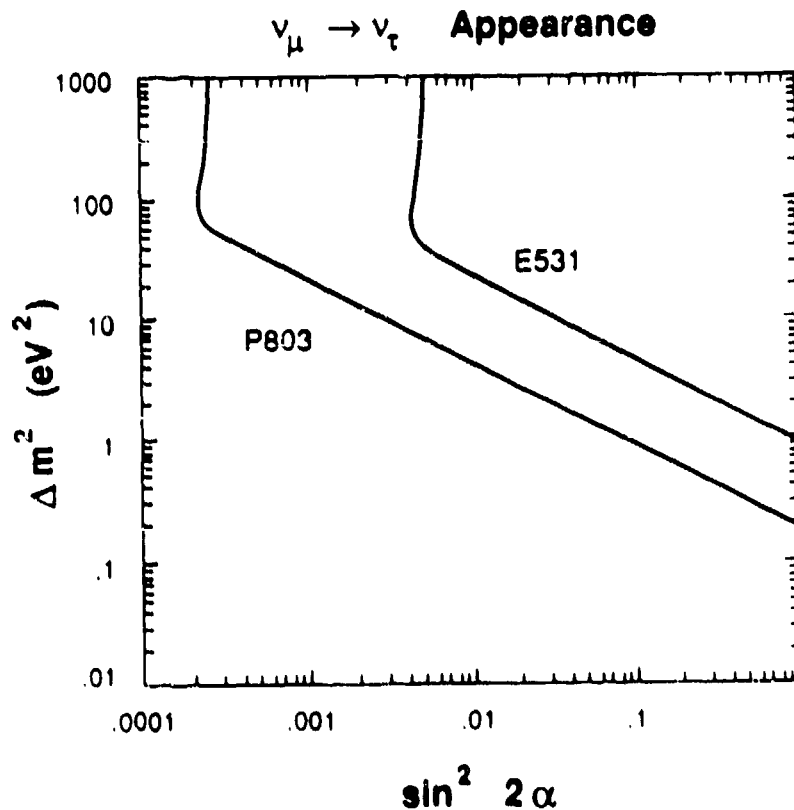


Figure 3

ν_μ DISAPPEARANCE

The principal interest in ν_μ disappearance experiments at this time is in the possibility of oscillation to ν_τ . Direct searches are limited in Δm^2 mass range by the neutrino energy needed to produce charged current events. No such limit is imposed on disappearance experiments. Unfortunately the systematic problems of understanding neutrino beams seem to limit the sensitivity of the searches to a few percent mixing. There are three experiments CCFR (Fermilab)⁽¹¹⁾, and CDHSW⁽¹²⁾, CHARM (CERN)⁽¹³⁾. Beam source at Fermilab was a normal focused beam $\langle E_\nu \rangle \sim 20$ GeV and the experiment utilized detectors at 110m and 700m. At CERN an unfocused beam from the PS was used with detectors at 120m and 900m. The exclusion curve looks somewhat like the curve described in the introduction, with the addition that at high Δm^2 the sensitivity falls off because finite experimental resolution means that the many oscillations that would occur between the detectors cannot be resolved. The limits achieved by these experiments are shown in Fig. 4.

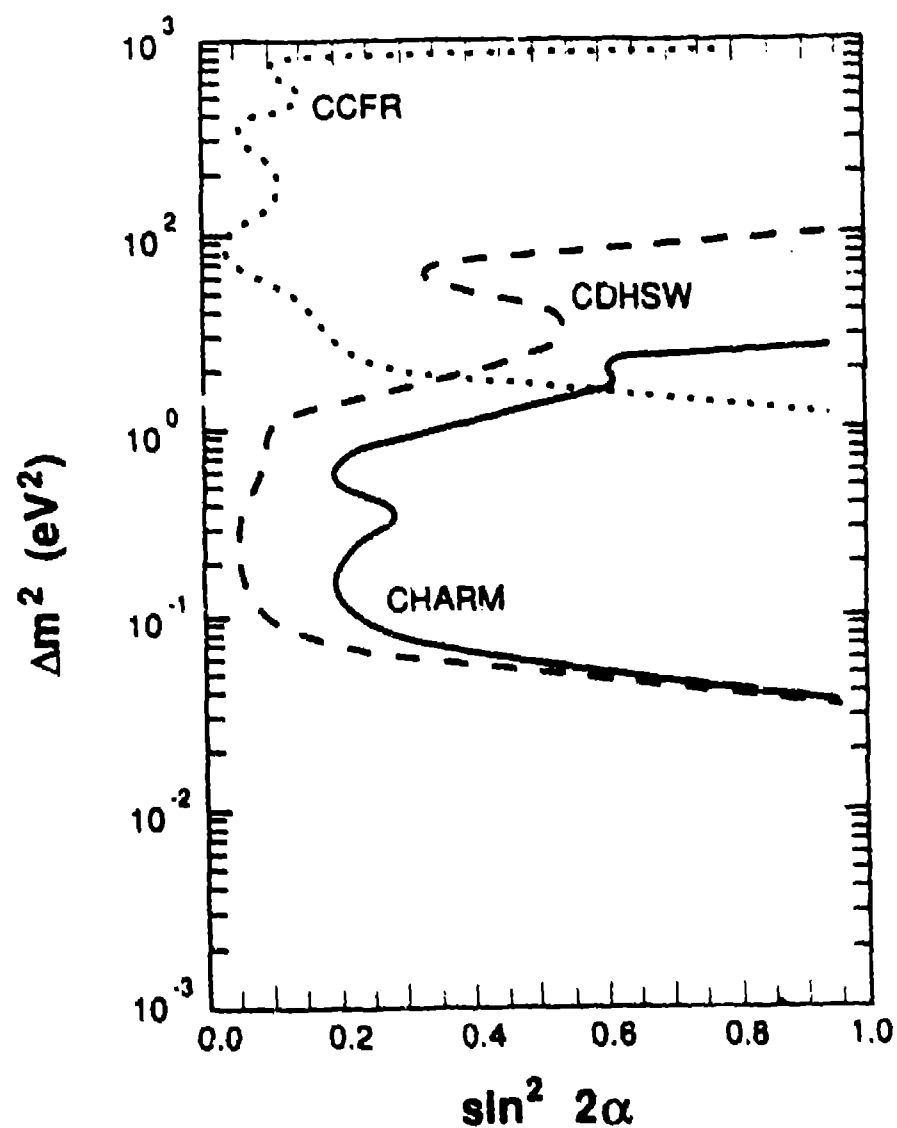
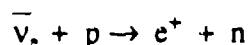


Figure 4

$\bar{\nu}_e$ DISAPPEARANCE

Fission products from a reactor are neutron rich and so when the fission products decay $\bar{\nu}_e$ are produced. The energy of the neutrinos is generally low (a few MeV) but the flux is copious. Searches for neutrino oscillations in the disappearance mode have been made at reactors, the two most recent being at the Bugey reactor in France and the Gosgen reactor in Switzerland⁽¹⁴⁾. The systematic problems that are common to these experiments is that the source of neutrinos is large physically and the intensity distribution changes with time. Reactors are monitored in detail and the conviction is that the luminosity distribution is well known as a function of time. Measurements of the reaction



are made observing the positron directly, together with the subsequent capture of the neutron after thermalization in ^3He counters. The sum of the positron and the neutron proton mass difference gives the neutrino energy with good precision. The neutrino spectrum is measured at two distances giving a limit on $\bar{\nu}_e$ disappearance. There were conflicting results at first from the positron spectrum measured in a single detector at Bugey⁽¹⁵⁾, but now it is accepted that the dependence of flux on distance is compatible with no oscillations and the limit from the Gosgen measurement is also shown in Fig. 2. Initial studies for a 1000 ton detector using Gadolinium loaded liquid scintillator to observe thermal neutrons through the 8 MeV capture gamma rays are underway to extend the Δm^2 range down to 10^{-4} eV^2 with a power reactor.

ATMOSPHERIC NEUTRINOS

The large proton decay detectors at Frejus, IMB and Kamioka⁽¹⁶⁾ have observed events from neutrinos produced in atmospheric interactions of cosmic rays. The initial cosmic ray interactions are high in the atmosphere so that the dilute medium allows pion and muon decays to be complete. Because pion (+) decays produce a ν_μ and muon (+) decays produce ν_e and $\bar{\nu}_\mu$ the ratio of muon induced charged current events should be approximately twice those from ν_e . A detailed Monte Carlo gives 1.7 ± 0.15 for the ratio of muon induced vs electron induced events. This is agreed to by all three experiments. The experimental data are shown in Table III.

TABLE III

<u>Detector</u>	<u>Exposure</u>	<u>Total Events</u>	<u>Data/MC</u>
IMB	3.77	401	1.00 ± 0.05
Frejus	1.53	197	0.97 ± 0.07
Kamioka	2.80	265	0.83 ± 0.05

The exposure is in kiloton years. Frejus and Kamioka have published momentum distributions for muon like and electron like events in accord with Monte Carlo. An up down ratio for neutrinos is measured with significantly different l/E but at present the ratios are not statistically compelling. Here we have a three and one half standard deviation effect in one experiment and agreement in the others. One of the Kamioka collaborators who was present at the meeting was quoted "At the moment, the totality of atmospheric neutrino data

from the Frejus, IMB, and Kamioka detectors provide no compelling evidence for neutrino oscillations". That is probably where this issue should rest but if you want a space to watch...

SUMMARY

After more that a decade of work there remains no clear evidence for neutrino oscillations of any type from accelerators or reactors. The area of exclusion on the $\Delta m^2 - \sin^2(2\alpha)$ plot is large, but the conviction remains that any further experiments must be capable of extending this region by a major factor and be capable of keeping systematic effects well under control. Even so there are a number of well conceived experiments that propose to continue the struggle.

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